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HST *BVI* photometry of Triton and Proteus

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Abstract

BVI photometry of Triton and Proteus was derived from HST images taken in 1997. The VEGAMAG photometric technique was used. Triton was found to be brighter by a few percent than observations of the 1970's and 1980's, as expected due to the increasingly greater exposure of the bright south polar region. The leading side was also found to be brighter than the trailing side by 0.09 mag in all filters—50% larger than reported by Franz [Franz, O.G., 1981. Icarus 45, 602–606]. Contrary to our previous results [Pascu, D., et al., 1998. Bull. Am. Astron. Soc. 30, 1101], we found no episodic reddening. Our previous conclusions were based on an inaccurate early version of the Charge Transfer Efficiency (CTE) correction. The present result limits the start of the reddening event reported by Hicks and Buratti [Hicks, M.D., Buratti, B.J., 2004. Icarus 171, 210–218]. Our $(B-V)$ result of 0.70 ± 0.01 supports the global blueing described by Buratti et al. [Buratti, B.J., Goguen, J.D., Gibson, J., Mosher, J., 1994. Icarus 110, 303–314]. Our observations of July 1997 agree with the Voyager results and are among the bluest colors seen. We found Proteus somewhat brighter than earlier studies, but in good agreement with the recent value given by Karkoschka [Karkoschka, E., 2003. Icarus 162, 400–407]. A leading/trailing brightness asymmetry was detected for Proteus, with the leading side 0.1 mag brighter. The unique differences in action of the endogenic and exogenic processes on Triton and Proteus provides an opportunity to separate the endogenic and exogenic effects on Triton.

Keywords: Triton; Satellites, surfaces; Neptune, magnetosphere

1. Introduction

Triton is an enigmatic satellite—seemingly without a past. Its high inclination, retrograde orbit obscures its origin, while its active geology conceals its surface history and age. By comparison, Proteus is a primitive body, moving in an unremarkable orbit, whose ancient surface has been sculpted by collisions (Croft, 1992). While photometric studies of Proteus are both sparse and rudimentary (Thomas and Veverka, 1991; Karkoschka, 2003), those of Triton are more instructive and controversial as well as more numerous. These studies are concerned primarily with three phenomena: (1) a leading/trailing brightness asymmetry (Franz, 1981; Goguen et al., 1989; Lark et al., 1989; Hillier et al., 1990, 1991; Cobb et al., 2001; Young and Stern, 2001; Herbert et al., 2003; Schmidt et al., 2003), (2) unpredictable episodic reddenings (Cruikshank et al., 1979; Buratti et al., 1994, 1999; Hicks and Buratti, 2004), (3) a secular global blueing (Buratti et al., 1994; Hicks and Buratti, 2004). We report on a new photometric analysis of HST *BVI* observations from 1997 whose results have a bearing on these three issues.

Our photometric analysis is based on 39 WFPC2 frames of Triton and Proteus taken in three visits—two on 3 July, and one on 6 July 1997. Each set of 13 frames was identical, with three *B* (F439W), five *V* (F555W), and five *I* (F791W) frames of

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Table 1
Triton *BVI* magnitudes and colors

Date	$B(1,0)$	$V(1,0)$	$I(1,0)$	pV	$(B-V)$	$(V-I)$
Visit 1 7/3/97 Leading: WE−19°	−0.646 (±0.009)	−1.343 (±0.002)	−2.119 (±0.006)	0.84 (±0.01)	+0.697 (±0.009)	+0.776 (±0.006)
Visit 2 7/3/97 Leading: WE−3°	−0.637 (±0.014)	−1.332 (±0.001)	−2.088 (±0.004)	0.83 (±0.01)	+0.695 (±0.014)	+0.756 (±0.004)
Visit 3 7/6/97 Trailing: EE−10°	−0.556 (±0.005)	−1.255 (±0.004)	−2.031 (±0.006)	0.78 (±0.01)	+0.699 (±0.006)	+0.776 (±0.007)

Note. EE = eastern elongation, WE = western elongation.

Table 2
Triton leading/trailing brightness asymmetry (trailing–leading)

Position	ΔB	ΔV	ΔI
3–1 Trail–lead	+0.090 (±0.010)	+0.088 (±0.004)	+0.088 (±0.008)
3–2 Trail–lead	+0.081 (±0.015)	+0.077 (±0.004)	+0.057 (±0.007)

varying exposures (Pascu et al., 2004). Our initial strategy was to relate the photometry of Proteus to ground-based photometry of Triton on the shorter exposures, and then the fainter satellites to Proteus on the longer exposures. Our initial results (Pascu et al., 1998) indicated a leading/trailing brightness asymmetry for Triton and large color difference between Triton and Proteus. This color difference in $(B-V)$ and $(V-I)$ suggested an episodic reddening of Triton.

While our previous reductions were done differentially, and involved image modeling, our present analysis uses aperture measurements only, and reduction with the VEGAMAG system (Bohlin and Gilliland, 2004). Significant corrections were necessary for distortion and charge-transfer efficiency (CTE) because of the extreme chip positions of Triton, and Neptune's halo light surrounding Proteus. The magnitudes were reduced to the *UBV(RI)* system.

2. Triton photometry

For Triton we measured only the eighteen frames which had unsaturated images of Triton; 2 in each filter, 6 in each orbital visit. An aperture of 25 × 25 pixels was used, with a 4-pixel border for estimating the background. The results are summarized in Tables 1 and 2. The solar phase function of Goguen et al. (1989) was assumed for reduction of V observations, and B and I observations as well. The geometric albedos in V were computed using −26.75 for the apparent V magnitude of the Sun (Livingston, 2000) and 1352.6 km as the radius of Triton (Davies et al., 1991). We use this radius rather than the more recently determined radius of 1353.4 km (Thomas, 2000) to be consistent with earlier workers. The newer value makes no difference in our photometric results, however.

What is immediately evident is the internal precision of the observations. However, since photometry with HST involves numerous corrections, some not well understood, systematic errors are always a possibility.

The most important result is that Triton did not experience an episodic reddening at the time of our observations, as had been reported earlier (Pascu et al., 1998). In fact, the mean value in $(B-V)=+0.70$, is compatible with ground-based and space-based values (Buratti et al., 1994; Hicks and Buratti, 2004). The $(V-I)$, likewise, shows no reddening, it being comparable to the Sun. However, the leading/trailing brightness asymmetry, reported by Franz (1981) remains, and amounts to about 0.09 mag in all filters.

3. Proteus photometry

The aperture measurements were considerably more difficult for Proteus due to its faintness, and because it was embedded in a halo background that was not linear. Much smaller apertures were necessary. Square apertures of 3, 5, 7, and 9 pixels were tried, with background borders of 1 to 4 pixels. The 5 and 7 pixel apertures, with one pixel borders were the most consistent. Centering issues with the 3 pixel apertures, and non-linear background for the 9 pixel apertures generally resulted in fainter magnitudes as expected. For Proteus, the advantage of the VEGAMAG photometry over the Triton-relative photometry is that Proteus' images on all 39 exposures—especially the long exposures—were available for measurement. The results are summarized in Tables 3 and 4. Despite the large CTE and aperture corrections, the internal precision is good.

The aperture photometry, reduced with the VEGAMAG system, appears to be more consistent and reliable than the differential photometry reported earlier. The reason for the earlier spurious color results was due to the use of an inaccurate early version of the CTE correction (4% wedge).

4. Discussion

4.1. Triton

Buratti et al. (1994) discuss the mechanisms which may be responsible for brightness and color changes on Triton. These

Table 3
Proteus *BVI* magnitudes and colors

Date	$B(1,0)$	$V(1,0)$	$I(1,0)$	pV[a]	$(B-V)$	$(V-I)$
Visit 1	+5.85	+5.13	+4.40		+0.72	+0.73
7/3/97	(±0.02)	(±0.01)	(±0.05)		(±0.02)	(±0.05)
Leading: EE−33°						
In orbit plane at EE	+5.81	+5.09	+4.36	0.093		
	(±0.02)	(±0.01)	(±0.05)	(±0.001)		
Visit 2	+5.86	+5.16	+4.42		+0.71	+0.74
7/3/97	(±0.02)	(±0.02)	(±0.03)		(±0.03)	(±0.04)
Leading: EE+54°						
In orbit plane at EE	+5.80	+5.09	+4.35	0.093		
	(±0.02)	(±0.02)	(±0.03)	(±0.001)		
Visit 3	+5.97	+5.26	+4.52		+0.72	+0.74
7/6/97	(±0.02)	(±0.02)	(±0.05)		(±0.05)	(±0.05)
Trailing: WE+59°						
In orbit plane at WE	+5.90	+5.19	+4.45	0.084		
	(±0.02)	(±0.02)	(±0.05)	(±0.001)		

[a] Using effective elongation radius of 210.8 km.

Table 4
Proteus leading/trailing brightness asymmetry (trailing–leading)

Position	ΔB	ΔV	ΔI
3–1	+0.12	+0.13	+0.12
Trail–lead	(±0.03)	(±0.02)	(±0.07)
3–2	+0.11	+0.10	+0.10
Trail–lead	(±0.03)	(±0.03)	(±0.06)

include the geometric effect of the changing subearth latitude, and the changing subsolar latitude which gives rise to endogenic processes such as geological events like geysers or volcanic activity or seasonal changes. Also involved are the exogenic mechanisms of bombardment by neutral meteoroids and charged micrometeor and heavy ion bombardment. Below we discuss how our results relate to these processes and how they fit in with previous (historical) results for Triton.

4.1.1. Magnitude/albedo

Table 1 summarizes our magnitude and albedo results for Triton, while Table 5 compares them with selected older as well as more recent results. Our error bars on the albedo are due to the photometry only, but the same dimensions were used for all albedo calculations.

The subearth latitude changed from about −34° in 1977, to −44° in 1989 at the Voyager encounter, to −49.6° for our observations in 1997. This change has increasingly exposed a larger portion of the bright south polar region, which in our observations dominates both the leading and trailing hemispheres. The increase in the V albedo from the late 70's to the present,

Table 5
Comparison of Triton magnitudes and colors

Study	$B(1,0)$	$V(1,0)$	$I(1,0)$	pV	$(B-V)$	$(V-I)$
This study;	−0.64	−1.34	−2.10	0.84	+0.696	+0.766
leading side WE	(±0.01)	(±0.01)	(±0.01)	(±0.01)	(±0.009)	(±0.006)
This study;	−0.56	−1.26	−2.03	0.78	+0.699	+0.776
trailing side EE	(±0.01)	(±0.01)	(±0.01)	(±0.01)	(±0.006)	(±0.007)
Franz (1981)	−0.48	−1.22	–	0.75	+0.74	–
	(±0.03)	(±0.02)		(+0.02, −0.01)	(±0.03)	
Lark et al. (1989)	–	−1.24	–	0.77	–	–
		(±0.02)		(+0.01, −0.02)		
Goguen et al. (1989)	–	−1.24	–	0.77	–	–
		(±0.04)		(+0.02, −0.03)		
Voyager: Nelson et al. (1990)	–	–	–	0.81	–	–
				(±0.08)		
Buratti et al. (1994),	–	–	–	0.80	+0.69	–
extrapolated to 1997				(±0.05)	(±0.01)	
Hicks and Buratti (2004)	–	–	–	0.80	+0.78	+0.80
				(±0.06)	(±0.04)	(±0.02)

evident in Table 5, is small but significant, and due most likely to this increased exposure of the high albedo south polar region.

4.1.2. Leading/trailing brightness asymmetry

Table 2 summarizes our results for Triton's leading/trailing brightness asymmetry. In Triton's case the leading side is brighter by 0.09 mag in all filters. This is 50% larger than that reported by Franz (1981), and by Hillier et al. (1991) from Voyager observations. It is also twice their predicted value for a subobserver latitude of $-50°$.

Most satellites lacking a significant atmosphere will display a leading/trailing brightness asymmetry. And for most of those satellites the source of the asymmetry is exogenic and involves the leading-side bombardment by neutrals and trailing-side bombardment by heavy ions. This may not be the case for Triton, however. Triton's surface is so variegated (Smith et al., 1989) and its light curve so unusual (Hillier et al., 1991) than an endogenic origin is more likely. On the other hand, the near 180° separation of the maximum and minimum in the light curve suggests an exogenic component as well.

4.1.3. Color

The history of Triton's $B–V$ color is summarized in Fig. 1. This expands on Fig. 5 of Buratti et al. (1994) and includes the data from the observations reported here. Our data supports the secular "blueing" observed since the 1952 data point of Harris (1961), however it appears to have been reversed by the reddening episode in 1997 (Hicks and Buratti, 2004), two months after the data reported here were taken. Note that no similar reddening was observed after the 1977 episode (Cruikshank et al., 1979; as cited in Buratti et al., 1999). Smith et al. (1989) describe the south polar cap as "reddish" in the Voyager images. It is puzzling, thus, why the color of Triton becomes "bluer" as more of the "reddish" polar region is exposed. Processes which might reduce $(B–V)$, such as the formation of small aerosol particles or frost grains on the surface, would be necessary to overcome the expected "reddening" trend. A possible source of such material would be fresh nitrogen frost deposits which could originate from cryovolcanic eruptions.

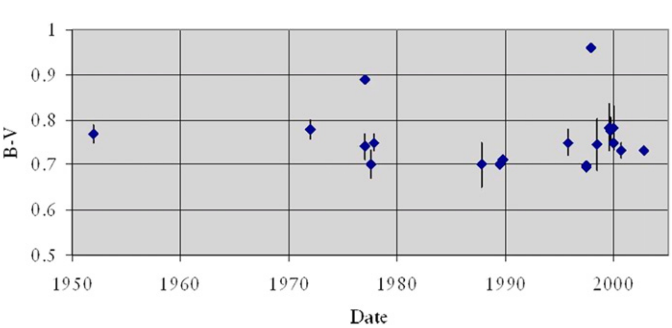

Fig. 1. Summary of $B–V$ color observations of Triton. Redder colors result in higher values of $B–V$. Note the very red colors observed in 1977 and 1997—the latter occurrence only two months after the data reported here (which are among the bluest colors reported). Note that points at 1995.6 and 2002.8 are calculated from reflectance spectra published by Tryka and Bosh (1999) and by Marchi et al. (2004), respectively.

The Voyager flyby only imaged the southern hemisphere of Triton, but even this limited view showed a moon atypical of the icy outer planet satellites with at least eight distinctive surface types (see Fig. 31 of Smith et al., 1989). The images showed "geyser-like plumes" near the south pole as well, apparently spewing dark material into the atmosphere. Fig. 1 shows that the flyby in 1989 occurred during a time of relatively normal color—we speculate that the reddening episodes of 1977 and 1997 may be the result of increased activity of such geysers.

Our negative reddening results fixes the maximum duration of the 1997 episodic reddening (Hicks and Buratti, 2004) as the interval between July 6, 1997 and May 9, 1998. In agreement with Hicks and Buratti, we also find no rotational color change in $(B–V)$ and $(V–I)$.

4.2. Proteus

As shown in Table 3, Proteus was found to be 0.5 mag brighter in V than reported by Voyager investigators (Thomas and Veverka, 1991), but our results are in good agreement with Karkoschka's (2003) reanalysis of the Voyager data—on the leading side only. Proteus, like Triton, was discovered to have a leading/trailing brightness asymmetry, in which the leading side was brightest; though for Proteus, the magnetosphere strikes the trailing face. The amplitude of this asymmetry was well determined and amounts to 0.1 mag in B, V, and I (Table 4).

Proteus was found to be quite neutral in color in these bands with no rotational color variation. While the $(B–V)$ of Proteus was the same as that of Triton, its $(V–I)$ was somewhat bluer.

Our results for Proteus indicate a leading/trailing brightness asymmetry consistent with ionic bombardment. Karkoschka's (2003) suggestion, that photometric differences were due to aspect differences of a non-spherical shape, is not supported by our results since the largest magnitude difference occurs at longitudes about 180° apart.

5. Future work

The leading/trailing brightness asymmetry for Triton and Proteus has some interesting implications for understanding exogenic mechanisms of surface modification in the Neptune system. Triton's relation to the two most important exogenic mechanisms—magnetospheric charged-particle bombardment, and gardening by neutrals (Johnson, 1990), is unique in the solar system. While the latter mechanism favors the leading face for all satellites, the former favors the trailing side for satellites in direct (prograde) orbits in systems with a substantial magnetosphere. Because of Triton's retrograde motion, however, Triton's leading face is bombarded by both neutrals and charged particles—its trailing side being spared much interaction with its environment. Proteus, on the other hand, has the more conventional interaction with Neptune's particle environment and is unlikely to have any endogenic sources of surface modification. Marchi et al. (2003, 2004) have detected substantial differences in the spectra of the leading and trailing sides of Triton—indicating differences in composition. A comparison of the spectra of Triton and Proteus may indicate the origin of the components of that environment, as well their identity.

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